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Stiffness-Based Assessment of Pavement Foundation Materials Using Portable Tools

Sarah R. Jersey and Lulu Edwards

Traditional pavement quality assurance has focused on soil density and moisture content. Implementation of new mechanistic design methods calls for measuring the resilient modulus of constructed layers to determine whether it matches the modulus used during the pavement design process. Several tools have been marketed for this purpose in recent years. Eleven soil test beds were constructed at the U.S. Army Engineer Research and Development Center to evaluate three of these tools. The study showed that the tools were simple to use and generally obtained repeatable results, but additional information regarding the true nature of the modulus measured by these tools was required to implement their use.

With the development and implementation of the Mechanistic–Empirical Pavement Design Guide, a renewed emphasis has been placed on characterizing pavement materials. In particular, attempts have been made to develop methods for characterizing subgrade and aggregate base materials in the field. Construction practice has historically been dominated by quantifying quality assurance in subgrade and base materials using moisture and density measurements. The design modulus is affected by the moisture and density; however, these are merely indicator variables and not predictors of the modulus. These parameters do not guarantee that the as-constructed stiffness will match the design stiffness. Thus, measuring density and moisture content in the field does not guarantee that the pavement foundation will perform as designed.

Recent developments have led to the marketing of several new portable tools for characterizing the modulus of subgrade soils and aggregate base materials in the field. These tools show potential as an alternative method of quality assurance during construction. This study is focused on the evaluation of the reliability and repeatability of three such tools for measuring the modulus of different soil types: the soil stiffness gauge (SSG), the light falling weight deflectometer (LFWD), and the portable seismic pavement analyzer (PSPA).

TEST DEVICES

Three portable tools for the measurement of soil stiffness were procured and used during this program: the SSG, LFWD, and PSPA. In addition, field California bearing ratio (CBR) and dynamic cone penetrometer (DCP) tests were performed in the same soils as they are typically performed in the field. These tests may be used to estimate the modulus.

Soil Stiffness Gauge

The SSG (Figure 1*a*) is a nondestructive method for measuring soil stiffness. The SSG is a lightweight device, weighing approximately 22 lbs and 11 in. in diameter and 10 in. tall. At the top of the device, there is an electronic display used to modify input parameters, change units, and control measurements. The bottom of the SSG contains a rigid foot in the shape of a 4.5 in. diameter annular ring.

During testing, the SSG induces vibrations through an electromagnetic shaker. The forces are imparted to the soil via the rigid cylinder and the rigid foot. The device cycles through 25 different frequencies ranging from 100 to 200 Hz. At each frequency, a shaker within the device induces a sinusoidal load pulse. Sensors in the foot measure the resulting force (P) and displacements (δ). A modulus value (E) is developed using Poisson's ratio (μ) and the ring diameter (R), as shown in Equation 1 (*1*). A value of 0.35 was assumed for Poisson's ratio when using the SSG.

$$E = \frac{1.78(1-\mu^2)P}{\pi\delta R} \tag{1}$$

At least 60% of the foot should be in contact with the ground. If proper contact cannot be maintained, the manufacturer suggests that the user should place a thin layer (approximately ⅛ to ¼ in. thick) of moist sand.

Light Falling Weight Deflectometer

The LFWD (Figure 1*b*) used in this study was developed in an effort to replace large in situ tests such as the plate-load test and the full-sized FWD. The principle of operation is based on the same concept as the full-sized FWD; a mass is dropped, and the resulting deformations at the ground surface are measured using one or more geophones.

The LFWD is approximately 4 ft tall, with a total mass of 57.3 lb. The device has drop masses of 22, 33, or 44 lb. The falling mass is lifted and dropped, allowing it to strike a rubber pad. The mass is dropped from a maximum height of 33.5 in. The adjustable height is used to vary the applied load in soils of differing stiffness. Larger drop masses and drop heights are used on stiffer soils. The drop mass impact produces a 15- to 20-ms load pulse, which is transferred to the ground surface via an adjustable load plate. The load plate may have a 4-, 8-, or 12-in. diameter. A load cell is placed directly above the plate

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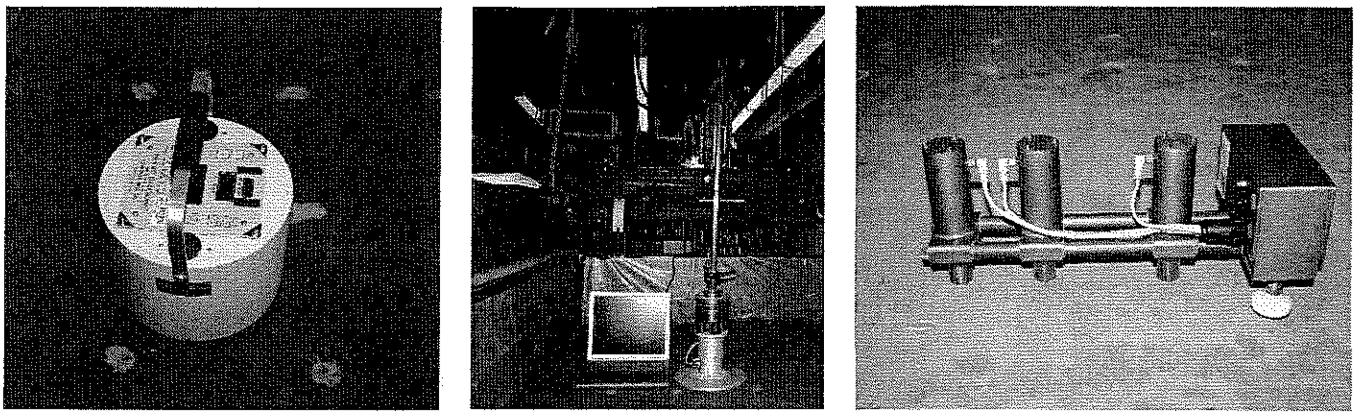

(a) (b) (c)

FIGURE 1 Portable tools used during this study: (a) soil stiffness gauge, (b) light falling weight deflectometer, and (c) portable seismic pavement analyzer.

to measure the maximum applied load from the drop mass. A geophone is located in the center of the load plate to measure the peak velocity response of the ground surface to the drop mass loading. In this study, the 22-lb drop mass and the 12-in. diameter plate were used. The modulus (E) was determined based on the applied load (P), plate radius (R), Poisson's ratio (μ), and the measured deflection at the center of the plate (δ), as shown in Equation 2 (*1*).

$$E = \frac{2(1-\mu^2)P}{\pi\delta R} \tag{2}$$

Portable Seismic Pavement Analyzer

The trailer-mounted seismic pavement analyzer was developed by the University of Texas at El Paso and the FHWA in the early 1990s as an alternative method for obtaining modulus in situ (*2*). This trailer-mounted device was similar to the FWD in terms of logistical footprint and test method. An alternative, lightweight portable system was developed based on the same technology. The result of this effort was the PSPA (Figure 1*c*). The basic elements of the PSPA are contained within 3 ft. The outer 2 ft consist of geophones used to measure surface wave velocity, whereas the inside 1 ft contains a hammer device that is used to induce ground movements or seismic waves. The PSPA was developed to characterize the modulus of the surface layer of a pavement system. This is accomplished by relating the surface wave velocity (V_R), Poisson's ratio (μ), and soil density (γ) to E by using Equation 3 (*3*). A value of 0.35 was assumed for Poisson's ratio this analysis. The details of this procedure are described by Nazarian et al. (*3*).

$$E = 2\gamma[1.13 - 0.16\mu]V_R^2 \tag{3}$$

HISTORICAL STUDIES

Many case histories have been reported in the literature. These studies investigated a variety of relevant test devices on several different soil types. Nine studies have been reviewed and summarized in Table 1.

The Minnesota Department of Transportation performed a study in which several portable devices were used to estimate modulus and were compared with compaction level at the Minnesota Road Research Project test facility (*4*). The DCP, SSG, and LFWD were tested in a gravelly base material and a sandy fill material. In general, a consistent trend between changes in compaction and changes in modulus across the wheel path was observed for each of the test devices in the gravel base. In the sandy fill material, changes in modulus were generally mirrored between the different devices; however, these changes did not follow measured changes in compaction. On the basis of these observations, the authors suggested that the portable devices could measure changes in compaction for a consistent material. There were significant deviations between the moduli reported by the individual devices. It should be noted that this LFWD differed from that used in this study.

Joh et al. examined the measurement of Young's modulus using spectral analysis of surface waves (SASW), the technology used in the PSPA, compared with the DCP, and the plate bearing test (*5*). They observed a general relationship between the DCP index and the measured shear wave velocity. Deviations were observed in gravelly subgrade materials.

The LFWD, DCP, and FWD were used in a laboratory and field study in Louisiana to obtain in situ modulus for pavement layers (*6*). The authors developed linear relationships between moduli obtained using the LFWD and the FWD. Incorporation of the void ratio and moisture content produced a better statistical relationship. A correlation also was developed between the LFWD modulus and the DCP index.

Sagrand et al. used the SSG to obtain modulus for cover material when backfilling during pipe installation (*7*). In looking at two backfill soils, a sand and crushed rock, they found that stiffness was a better indicator of backfill quality than the traditional measure of dry density and moisture content, because it could be related to the constrained modulus. They observed that the SSG overpredicted the in situ modulus and applied an empirical correction factor based on the backfill soil quality. This study showed little correlation between SSG modulus and dry unit weight.

The LFWD and DCP were used to analyze three different soil types in a field study by Lin et al. (*8*). They found that the larger-sized plate produced better results, whereas the drop height did not affect the modulus values. The sand and gravel moduli were more variable

TABLE 1 Summary of Historical Research

Study	Devices	Soils	Type of Study
Siekmeier et al. 2000 (*4*)	DCP SSG LFWD	Gravelly base Clayey and silty sand subgrade	Field
Joh et al. 2006 (*5*)	SASW DCP	21 subgrade materials Two subbase materials Nine base materials	Field
Nazzal et al. 2007 (*6*)	LFWD DCP FWD	Well-graded clayey gravel (GW-GC) Low plasticity clay (CL) Low plasticity silty clay (CL-ML) Poorly graded clayey gravel (GP-GC) Poorly graded silty gravel (GP-GM) Poorly graded sand (SP) Poorly graded gravel (GP)	Field Laboratory
Sargand et al. 2004 (*7*)	SSG	Crushed limestone Sand	Field
Lin et al. 2006 (8)	PFWD DCP CBR	Sandy clay Coarse gravel Sand	Field
Sawangsuriya et al. 2006 (9)	SSG Seismic	Sand (SP)	Laboratory
Flemming et al. 2007 (*10*)	LFWD	Sand	Laboratory
Rathje et al. 2006 (*11*)	PSPA SSG	High-plasticity clay (CH) Low-plasticity clay (CL) Well-graded sand (SW) Well-graded gravel (GP)	Field
Lenke et al. 2001 (*12*)	SSG	Sandy base Silty sand subgrade materials Lime stabilized sandy clay	Laboratory Field

than the clay, as were the DCP results. Modulus values obtained from the DCP were higher than those obtained from the LFWD.

Sawangsuriya et al. assessed the SSG as a method for measuring soil stiffness in sandy materials (*9*). A 2-ft-diameter, 1.7-ft-tall cylindrical mold was used for laboratory tests of stiffness for sandy soils deposited under a number of preparation methods. They found that the modulus obtained with the SSG was lower than that determined with seismic methods.

Flemming et al. performed a series of tests on sandy subgrade soils in the laboratory (*10*). LFWD and FWD moduli were difficult to correlate; this finding could be attributed to site-specific effects. The foot of the LFWD was not able to maintain adequate contact when used on weaker surfaces.

Rathje et al. performed an extensive study of nonnuclear methods for assessment of compaction (*11*). The SSG and PSPA were included in their initial study; however, the SSG was not used in the field. When dry densities were compared with PSPA moduli, significant variability was observed in the clayey soils, whereas trends were more consistent in sandy soils.

Lenke et al. examined the SSG as a method of conducting compaction control (*12*). They considered silty sands and stabilized sandy clay subgrades. Laboratory and field studies were performed for assessment of the ability of the SSG to observe changes in modulus caused by increased compactive effort. They found that the measured modulus increased after each roller pass. They also saw an increase in modulus in stabilized materials over 28 days after construction.

Historical studies have predominantly focused on applications to coarse-grained materials. Many studies reported a disconnect between moduli obtained with the various devices.

MATERIALS

Historical testing with these devices has been focused toward coarse-grained materials, with limited efforts on fine-grained materials. To cover the highly variable soil conditions that military engineers encounter, it was necessary to characterize both coarse- and fine-grained soils. In this study, several soil test sections were constructed, including two loose sands (SP, SP-SM) and three fine-grained materials (CH, CL, and ML). Each material was constructed at two moisture conditions. The grain size distributions for these materials are shown in Figure 2. Two test items were constructed for each soil type at different densities and moisture contents. The soil properties are summarized in Table 2.

LABORATORY INVESTIGATION

Test Facility

A 6-ft^2, 4.5-ft-deep reinforced steel box was fabricated as a containment facility for laboratory pavement test sections (Figure 3). The containment facility is composed of 1-in.-thick steel plates reinforced with ¼-in.-thick, 6-in.^{2} structural steel tubing along the bottom and three sides of the box.

The front of the facility is composed of removable ¼-in.-thick, 6-in.^{2} structural steel tubing. The front of the facility can be removed to facilitate the construction process. The tubes are bolted to the facility one layer at a time as construction proceeds, simplifying the process of placing and constructing the soil materials within the test facility. Before placement of the soil, the containment facility was lined with

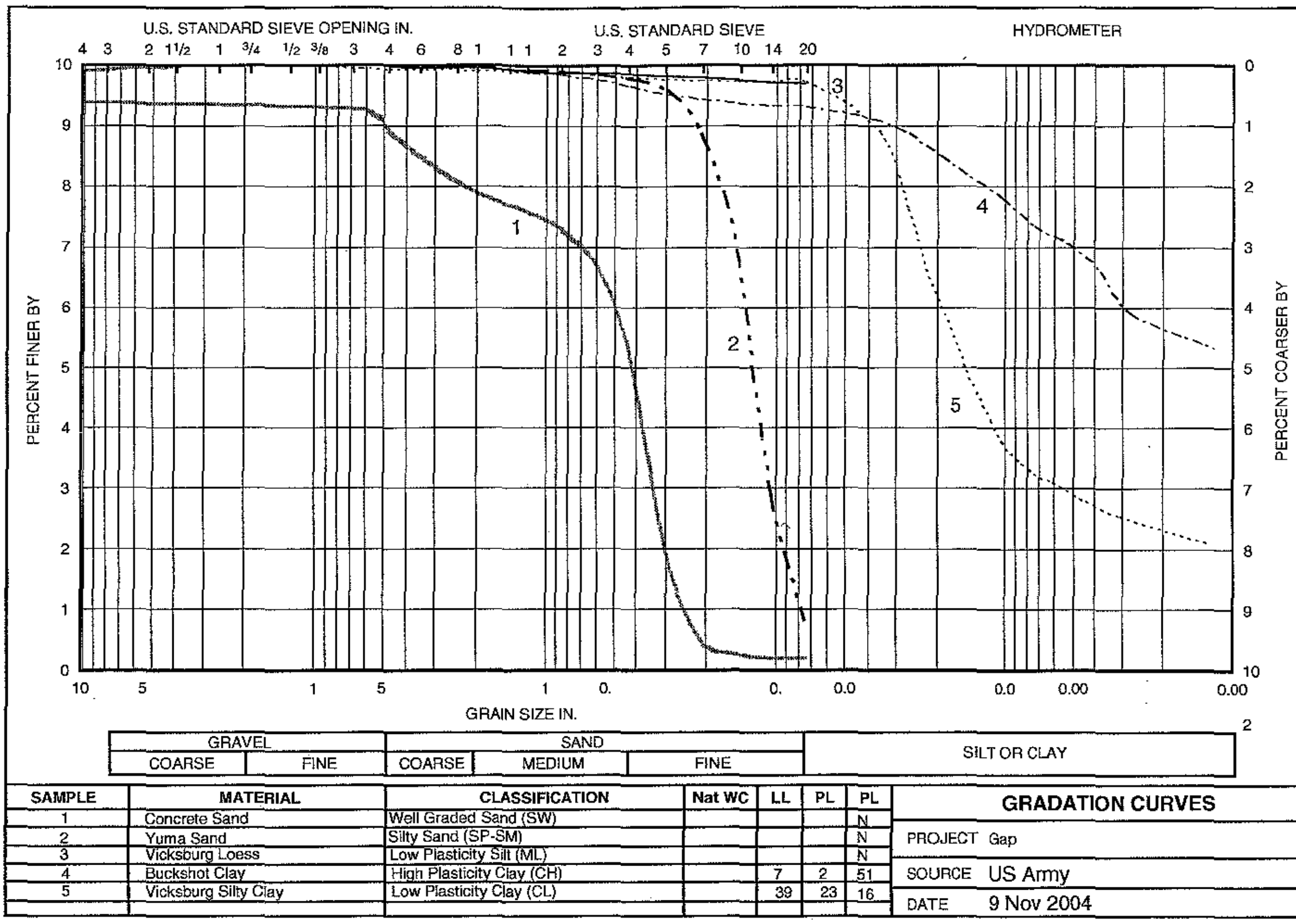

FIGURE 2 Grain size distributions of test soils.

polyethylene to minimize moisture migration and desiccation of the test items.

Test Section Construction

All soils used in this study were stored in stockpiles and covered with tarps to prevent rapid wetting and drying of the soils. In addition, the covers prevented the loss of significant amounts of fines because of wind action. Before soil preparation, an initial moisture content was measured. Several cubic feet of material were placed on a soil preparation strip. The soils were periodically mixed and spread out to obtain a uniform moisture content. Those soils wet of the desired moisture content were air dried and pulverized, whereas those soils dry of the desired moisture content were pulverized to break down clods and spread on the soil-processing strip. Soils were repeatedly mixed to obtain uniform moisture content.

The prepared soil was transported and deposited in the test facility using a skid steer loader. Soil was hand spread in the test facility to a uniform depth of 6 in. Coarse-grained soils were compacted by using a vibratory plate compactor, and fine-grained soils were compacted by using a pneumatic compactor. Construction quality control tests were taken before construction of the next lift. Tests included density and moisture tests using the nuclear density gauge, measurement of moisture content using both oven and microwave methods, and a survey of the surface. On construction of the final lift, a clean smooth surface

TABLE 2 Summary of Relevant Soil Properties

Soil No.	Name	Test Item	Soil Type (USCS)	Percent Gravel	Percent Fines	C_c	C_u	LL (%)	PL (%)	PI
1	Concrete sand	1-1, 1-2	SP	10.6	1.8	0.92	2.13	—	—	NP
2	Yuma sand	2-1, 2-2	SP-SM	0	7.9	1.05	1.79	—	—	NP
3	Vicksburg loess	3-1, 3-2	ML	0	97.2	—	—	—	—	NP
4	Buckshot clay	4-1, 4-2	CH	0	93.5	—	—	74	23	51
5	Vicksburg silty clay	5-1, 5-2	CL	0	97.2	—	—	39	23	16

NOTE: C_c = coefficient of curvature; C_u = coefficient of uniformity; LL = liquid limit; PL = plastic limit; PI = plasticity index; USCS = United Soil Classification System.

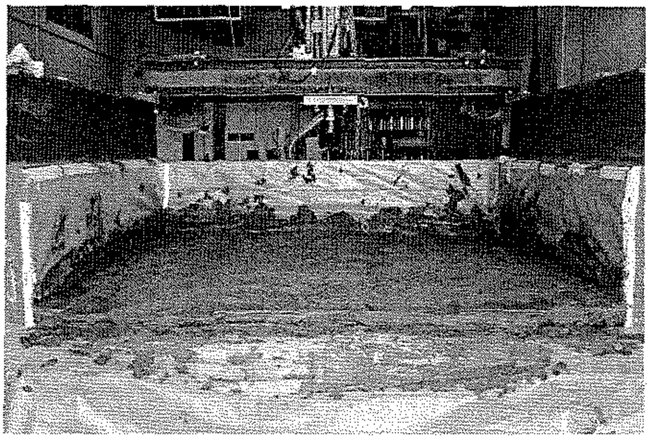

FIGURE 3 Laboratory soil containment facility.

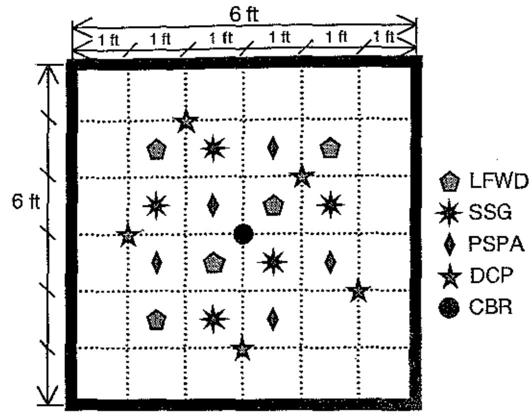

FIGURE 4 Schematic of test layout.

was trimmed, and a 1-ft grid was laid out on the surface. Each test item was constructed to a soil depth of 3 ft. Measured densities and moisture contents are summarized in Table 3. The nuclear densometer was used before collecting samples for oven and microwave moisture tests. Item 1-1 was a well-draining material, compacted moist of optimum. The free drainage and lack of fines in this material resulted in a significant difference between the moistures obtained using the nuclear densometer and the oven and microwave methods because of water migration between nuclear densometer testing and sampling for the oven and microwave methods.

Testing

A series of in situ tests was performed on each test item: CBR, DCP, portable FWD, SSG, and PSPA. Portable tools were tested at a distance of at least 1.5 ft from the wall with the exception of the DCP. DCP tests were run at least 1 ft from the wall. These conditions were imposed to prevent the introduction of an artificial boundary condition into the testing. The method by which modulus values are calculated assumes a linear elastic, isotropic, half-space. The presence of the wall within the zone of influence violates this assumption. In terms of depth, each tool has a depth of influence associated with it: 9 to 18 in. for the SSG (*12*), 12 to 15 in. for the LFWD (*13*), and up to 24 in. for the PSPA. With the PSPA, the modulus is calculated at several depths using the dispersion curves (*3*); however, the output will be based on a test depth requested by the user. The test layout is shown in Figure 4. For each of these test methods, a number of replicates were performed across the test pavement facility. These replicates are summarized in Table 4. The tools were used in the same order and at the same locations on every test item. This order was chosen to minimize disturbances and effects between test devices while maximizing the number of tests performed.

First, nondestructive, surficial tests were performed. These test devices were used first because they require an undisturbed surface to properly estimate modulus, particularly in the loose, coarse-grained soils. These devices produced only minimal surface disturbances, leaving the test item surface in good condition for further destructive tests. These devices were the PSPA, LFWD, and SSG.

Next, DCP tests were performed. These tests involve the insertion of a probe into the ground, resulting in a more severe disturbance in the zone surrounding the test. After completion of the DCP, an in situ CBR test (CBR_{field}) was performed in the center of the box at the soil surface. This center zone was left undisturbed by the other tests. Because of the potential surface disturbances associated with the setup of the field CBR apparatus and the limited test area in the containment facility, it was necessary for the CBR test to be conducted last.

RESULTS AND DISCUSSION

The results obtained with various stiffness devices are displayed in Figure 5. In terms of measured moduli, the SSG and LFWD behaved similarly but were of different magnitude, the exception

TABLE 3 Representative Soil Moistures and Densities

Test Item	Soil Type (USCS)	Wet Density (pcf)	Dry Density (pcf)	Moisture (%)	Oven Moisture (%)	Microwave Moisture (%)
Item 1-1	SP	119.5	107.4	11.31	8.7	8.6
Item 1-2	SP	110.2	106.0	4.0	4.9	4.6
Item 2-1	SP-SM	107.0	99.4	7.7	8.5	8.1
Item 2-2	SP-SM	100.0	94.4	2.7	4.5	4.3
Item 3-1	ML	122.8	104.9	17.1	18.1	18.0
Item 3-2	ML	121.5	100.4	21.1	21.3	21.7
Item 3-3	ML	123.9	103.8	19.1	18.5	19.2
Item 4-1	CH	112.7	80.9	39.2	36.1	36.6
Item 4-2	CH	106.1	75.1	43.6	45.2	46.3
Item 5-1	CL	106.3	88.3	20.1	20.8	20.4
Item 5-2	CL	115.9	90.8	27.5	27.3	27.2

TABLE 4 Summary of Testing Protocol

Test Number	Test Method	Test Locations	Test Replications
1	PSPA	5	5 replicates per location
2	LFWD	5	6 drops per location
3	SSG	5	3 replicates per location
4	DCP	5	1 full depth penetration per location
5	CBR	1	3 replicates per location

being Item 3-2. The SSG sensors were overranged on Item 3-3; the modulus was too low to measure. PSPA moduli followed similar trends to the SSG and LFWD in the coarse-grained material (Items 1 and 2) but were approximately twice the magnitude. There was no trend observed in PSPA moduli in fine-grained materials (Items 3, 4, and 5).

The variability of the tested devices is shown in Figure 6. All three devices showed significant variability between tests on an individual test item, as measured by the coefficient of variation (COV) of the modulus. The SSG showed less variability overall, COV of 3% to 6% in coarse-grained materials and COV of 11% to 38% in fine-grained materials. In the coarse-grained materials, the LFWD showed little variability (7%–8% COV), whereas significantly more variability was observed in the fine-grained materials (4%–69% COV). COV values for PSPA measurements were 10% to 21% for coarse-grained materials and 7% to 36% for fine-grained materials. Measurements were repeatable within the same location for the LFWD and PSPA but varied between test locations, leading to high COVs. In general, because of the inherent heterogeneous nature of soils, variability is expected. It has been reported that a COV of 30% is considered standard for measurements of elastic modulus in soil testing, whereas typical values of COV are considered to fall within the range of 2% to 42% (*14*). Thus, the measured variability within a test section was generally acceptable with the exception of the LFWD in the very soft silt.

It is suspected that the fine-grained materials exhibited greater variability because of issues associated with obtaining a level testing surface. The surface was rough after being compacted using the pneumatic hammer. To maintain full contact in the softer materials, a flat surface had to be specially prepared by removing the top 1 in.

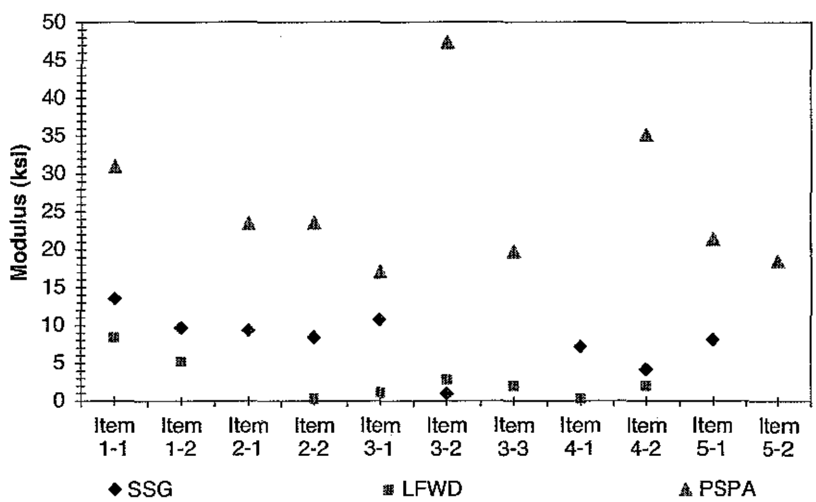

FIGURE 5 Modulus measured with the three devices (ksi = kilo-pound force per in.^{2}).

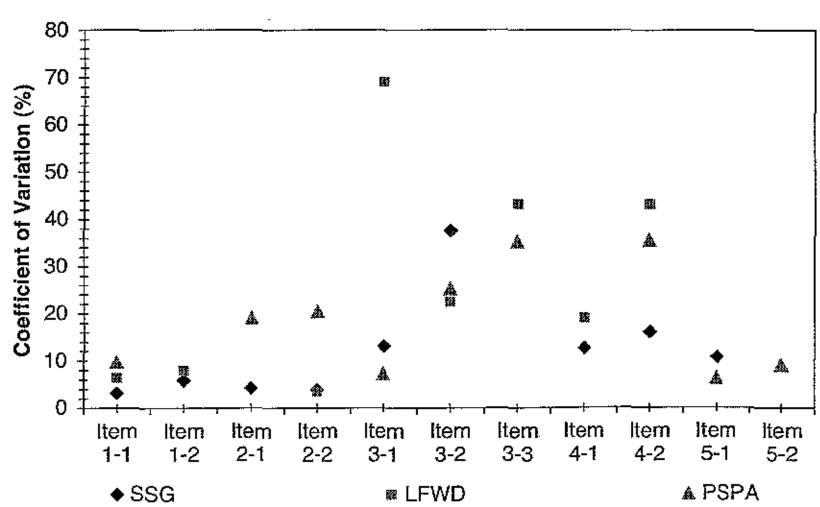

FIGURE 6 Variability of modulus measurements.

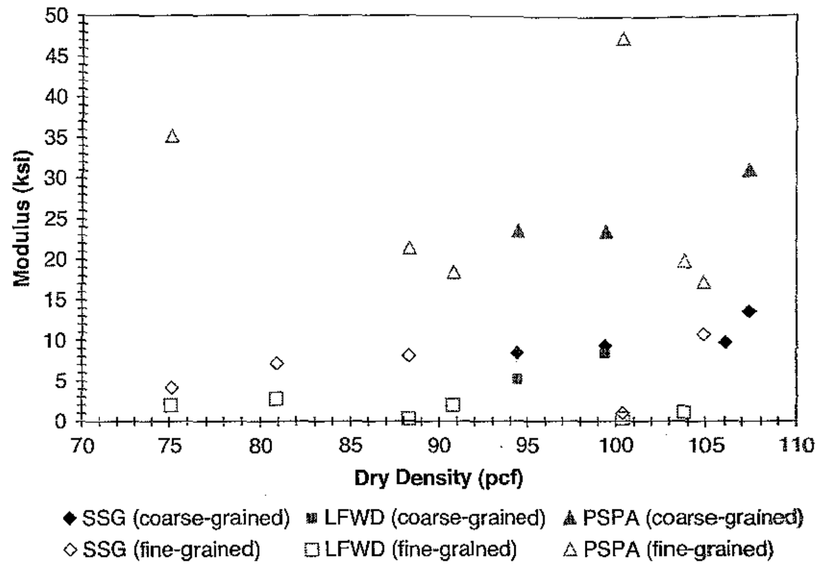

FIGURE 7 Relationship between dry density and modulus, as measured by test devices.

of soil with a shovel. The difficulty associated with providing a smooth, undamaged test surface in the soft materials may have led to increased variability of the results. In addition, the soft fine-grained soils showed more pronounced changes in modulus near the wall than the coarse-grained sandy materials. There was no discernable trend in values near the wall for an individual soil type or an individual testing device. In some cases, measured values of modulus increased and in other cases modulus values decreased near the wall. It is hypothesized that this variability is caused by the heterogeneity of soils and the difficulty associated with compacting a moist fine-grained soil near the boundary. This finding has implications for compaction control of fine-grained soils near underground structures.

As noted previously, moisture and density have historically been used as indicators of compaction in the field. Figures 7 and 8 show the moduli measured with the different portable devices relative to the measured dry density and moisture content. Each test point is denoted as coarse or fine grained. The moduli decreased with increasing moisture content and decreasing dry density, as expected. From these plots, it is apparent that there is no singular relationship between the field density or moisture and the measured modulus. A more complex model incorporating additional soil parameters is recommended.

Webster et al.'s relationships (*15*) were used to convert DCP index (penetration rate) into CBR and are described in Equations 4, 5, and 6:

$$CBR_{DCP} = \frac{292}{PR^{1.12}} \tag{4}$$

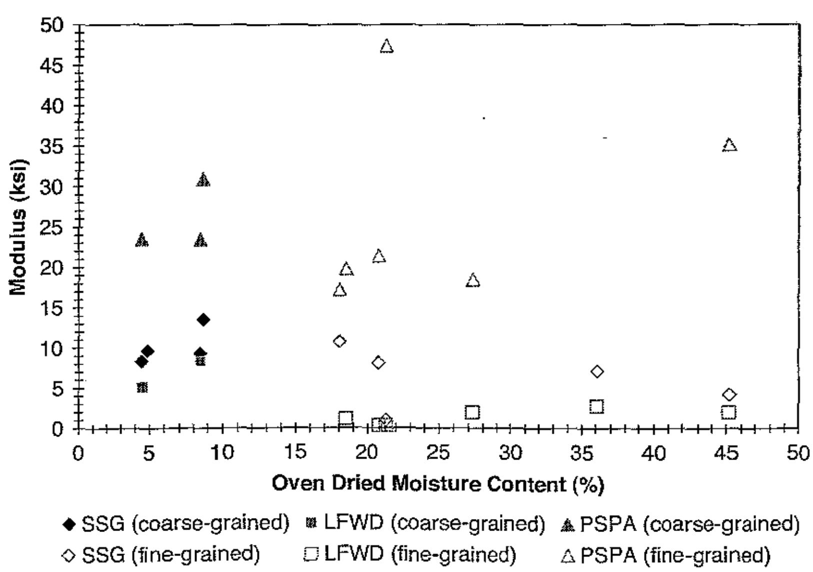

FIGURE 8 Relationship between oven-dried moisture and modulus, as measured by test devices.

$$\mathrm{CBR_{DCP}} = \frac{348}{\mathrm{PR}} \tag{5}$$

$$\mathrm{CBR_{DCP}} = \frac{3{,}452}{\mathrm{PR}^2} \tag{6}$$

where PR is penetration ratio.

In these equations, the DCP index should be measured in mm/blow. Equation 4 is the general equation for all soils, whereas Equation 5 is used for high plasticity clays. Equation 6 is recommended for low plasticity clays. For each 6-in. lift, a representative $\mathrm{CBR_{DCP}}$ was obtained. The coarse-grained soils (Items 1 and 2) exhibited increasing strength with increasing penetration depth, as expected for these types of materials. The high plasticity clay test items also showed an increase in CBR with depth, characteristic of adhesion between the rod and the clay.

Powell et al. suggested Equation 7 for estimating a modulus value based on the CBR strength (*16*):

$$E(\mathrm{psi}) = 2{,}550\mathrm{CBR}^{0.64} \tag{7}$$

Figure 9 shows the modulus obtained from each test device compared with the modulus estimated from the DCP test. This figure suggests that the SSG and LFWD predict modulus values of the same order as that estimated by the strength, whereas the PSPA predicts significantly larger values.

The nonlinear nature of soils plays a critical role in the assessment of a modulus value for a soil. This nonlinearity makes characterization of a modulus value difficult. Thus, one must determine at what strain level the modulus should be quantified: the initial modulus, the modulus at a specific strain level, or perhaps at a specific percentage of the failure load. It can be difficult to interpret the measured modulus values.

An analysis of the strain level at which each device obtains the modulus value sheds additional light on the results. The DCP and LFWD impart greater strains than the PSPA and SSG, suggesting that the modulus values obtained with these two devices should be of a lower magnitude. The PSPA imparts a very small strain; therefore the modulus values obtained with the PSPA should be of a greater magnitude. Generally, this was observed in Figure 9; the PSPA showed greater modulus values than any other tool, including those values estimated using Powell et al.'s equation. The figure also highlights the need for laboratory calibration with an accepted modulus test such as the resilient modulus to quantify values in the field.

CONCLUSIONS AND RECOMMENDATIONS

A series of tests was performed using three portable devices for measuring soil modulus. Each test device was used on five different soil types at various moisture and density levels, producing a test matrix of 11 test soils. The conclusions and results derived from this analysis are summarized as follows:

1. The variability observed during testing suggests that the tools produce results with acceptable variability considering the inherent heterogeneous nature of soil deposits.
2. These tools are not recommended as the sole means of obtaining quality assurance–quality control parameters. Site-specific verification in the field to determine the modulus level considered adequate for construction purposes is recommended at this time. Users should be cautious when utilizing values obtained with these tools, ensuring that they are aware that these values represent effective moduli rather than the modulus from laboratory testing.
3. Because of the high variability observed during this study and the difficulty associated with obtaining a sufficiently flat location for testing, these devices are not recommended for soft, fine-grained soils that are placed moist of optimum.
4. These portable tools should be used with caution near subsurface boundaries such as pipes and foundations, because stiffness values may be affected at distances less than 1 ft from the boundary.
5. Further studies are needed to asses the capability of these devices in stiffer fine-grained soils because literature has focused primarily on base course type materials.
6. More detailed studies need to be performed over a variety of soils to develop a relationship between estimated field modulus and the modulus used for mechanistic design. Additional laboratory studies are required to calibrate the field modulus with the resilient modulus value used in pavement design.

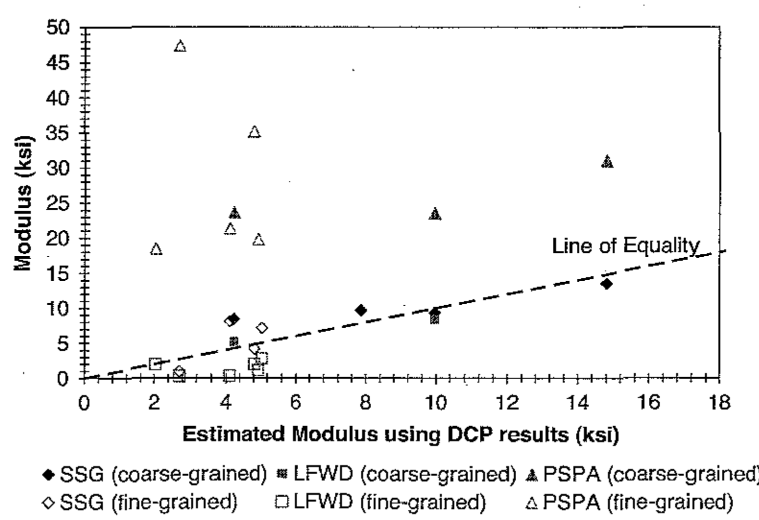

FIGURE 9 Relationship between modulus estimated from dynamic cone penetrometer and modulus measured using portable test devices.

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